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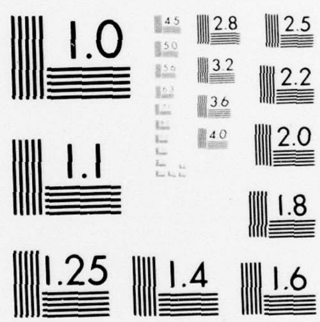

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A TWO DIMENSIONAL ELECTRONICALLY FOCUSED IMAGING SYSTEM*

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ABSTRACT. ~~We have constructed~~ a two dimensional acoustic imaging device, with electronic focusing and scanning in both directions. WAS CONSTRUCTED The device is designed to work with 2.25 MHz acoustic waves. It employs M piezoelectric elements in a transmitting transducer, which produce a beam focused and scanned in the y direction. An N element receiving transducer is used to focus and scan in the x direction. This makes it possible to obtain M × N resolvable spots with only M + N elements, a considerably saving in complexity. The phase reference for the transmitter and receiver are supplied by frequency modulated chirp signals sent along acoustic surface wave delay lines. One of the novel features of this device is the ability to obtain an arbitrary scan velocity, even a stationary focus, with the transmitter.

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At the present time we are testing a 100 element linear array and a two dimensional 22 × 29 element system. With the latter system, we have demonstrated a stationary focus and a slowly scanned transmitted and focused beam, and are obtaining two dimensional electronically focused images.

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I. Introduction

At last year's Ultrasonics Symposium, we described an electronically focused and scanned receiver system capable of a resolution of approximately 1 mm at a distance of 20 cm using 5 MHz acoustic waves.[1] The device used an array of piezoelectric transducers with a phase reference for each transducer obtained from a corresponding tap on an acoustic surface wave delay line, along which was propagated a linear FM chirp signal. The signals from each tap and the corresponding piezoelectric transducer are mixed, and the output from the receiver array taken at the sum frequency of the acoustic signal and the signal sent along the delay line. The scan velocity was determined by the acoustic surface wave velocity and the focal length of the electronic lens by the chirp rate. By using mechanical scanning in one direction and electronic scanning and focusing in the other, we were able to obtain good images of small objects with a 30-element array.

Since that time, we have been developing a 100-element one-dimensional array. Our aim was to obtain far better sensitivity with approximately 2 mm resolution at a distance of 20 cm and a frequency of 2.25 MHz. To this end, we have been constructing a system with amplifiers on every delay line tap and amplifiers on every element of the PZT array, with the two outputs feeding balanced mixers to eliminate spurious signals. This system appears to be capable of a sensitivity of approximately 10^{-11} watt/cm^2. At the present time, a 100-element array consisting of elements 0.4 mm and 0.5 mm square has been constructed and tested. It has an acceptance angle of approximately $\pm 30^\circ$ in the x and y directions as required for our system. The circuits have all been assembled and the system is presently being tested. Early results indicate that the sensitivity is close to that measured for the individual elements and that good focusing can be obtained. It is intended, first, to obtain images by mechanically scanning a large transmitter and electronically scanning the receiver. Later, this receiver array will be incorporated with electronically focused and scanned transmitter. The advantage of this approach is that it uses only M + N elements to obtain M × N resolvable spots. This makes it far lower in cost and complexity than many other systems which can image M × N resolvable spots.

We describe here our experiments on and the theoretical principles of the electronically focused and scanned real-time system which is focused and scanned in both the x and y directions. The device makes use of a transmitter constructed in much the same way as the receiver, which focuses and scans in the y direction, the scan rate being at an arbitrary velocity which we can choose at will. The system uses a separate receiver focused and scanned in the x direction. Twenty-nine elements are used in the transmitter, and 22 elements in the receiver. The receiver makes use of an early developmental model of the 100-element array. With this device, we have obtained images focused and scanned in the x and y directions in real time.

II. Principles of the Two-Dimensional Focusing System

The basic components of the two-dimensional focusing system are shown in Fig. 1. The transmitter consists of an array of piezoelectric strip transducers which are excited from taps on an acoustic surface wave delay line. The transmitter emits a beam, focused and scanned in the y direction. So it acts like a cylindrical lens moving with a velocity v_y in the y direction producing a beam focused to a line in a plane at a distance z from the array.

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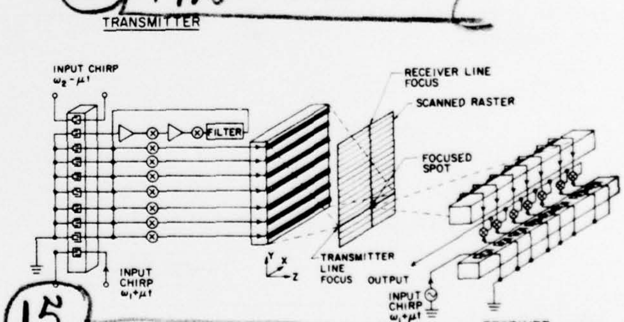

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FIG. 1--Schematic-pictorial diagram of an electronically scanned, electronically focused acoustic imaging device.

The receiver, which is of the type described in previous publications,[2,3,4] can be used in either a reflection or transmission mode and is focused on the same plane, but is scanned at a velocity v_x in the x direction. So it acts like a cylindrical lens,

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focused in the x direction, and moving with a velocity v_x in the x direction. The combination of the receiver and transmitter cylindrical lenses focuses on a spot which moves along a line and a plane with velocities v_x, v_y.

For the purposes of a demonstration of the principles of operation, we have worked with two alternative methods of scanning the system in a transmission mode. In the first, the scan rate of the transmitter is approximately the same as that of the receiver, so the spot scans lines at 45^o to the x axis. In the second, by using a combination of two chirps passing in the opposite directions in the transmitter, the scan velocity in the y direction can be made arbitrary, even zero, so that the y scan rate essentially controls the frame rate. Under these circumstances where $v_y \ll v_x$, the raster scanned is then just like that of a normal TV image, with the scan lines almost in the x direction, with a line time of approximately 100μsec and 60 cps frame rate.

This system is of fundamental importance because it demonstrates that the scan rate in either direction can be arbitrary. This means that we can use these devices as fixed focus lenses, or they could be used in sonar systems operating at frequencies in the 100 kHz range, with appropriate scan rates far below the value of 10^5 cm/sec used in our first devices, a velocity basically determined by the velocity of an acoustic surface wave.

A block diagram of the variable scan rate transmitter is shown in Fig. 2. The major change from the system described for the receiver and still used, with improvements, in this device are: (1) to operate the device with input signals in the delay line and take the outputs from the piezoelectric transducers, i.e., to operate it in a reciprocal fashion from that of the receiver, (2) to obtain an arbitrary scan velocity, chirp signals are inserted at each end of the delay line; the combination of these two chirps gives a phase variation along the line, which can be stationary or can be moved along the line with an arbitrary velocity, thus giving rise to a focused transmitted beam with a fixed focus or with a focal point which can be moved in a direction parallel to the array at an arbitrary velocity.

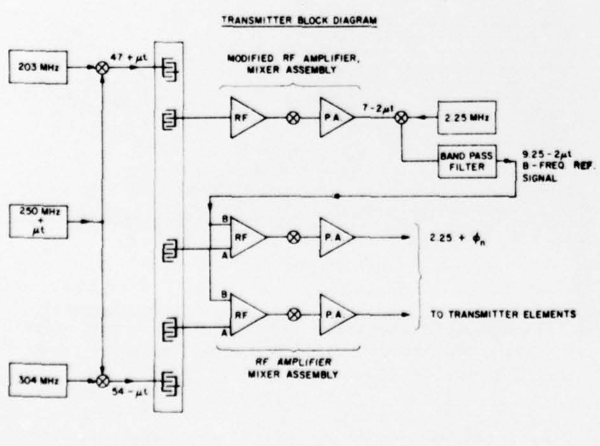


FIG. 2--Block diagram of the variable scan rate transmitter.

In physical terms, each chirp can be regarded as behaving like a lens, just as in the receiver, as illustrated in Fig. 3. One chirp alone would correspond to a lens of focal length f. Two chirps correspond to a lens of effective focal length $f/2$ from the array. Now suppose one lens was moved along a line, as does the signal transmitted along the delay line, the focal point would move in the x direction at the lens velocity. If, on the other hand, the two lenses were moved in opposite directions at the same velocity, it is not unreasonable to expect that, by symmetry, the focal point would not move. Thus we might expect two chirps moving in opposite directions to give rise to an acoustic beam with a fixed focus. Finally, if the center frequency of one chirp were changed slowly with time, this would be equivalent to moving the two lenses at slightly different velocities. Now the focal point would move in the y direction at a velocity determined by the rate of change of the center frequency of the chirp.

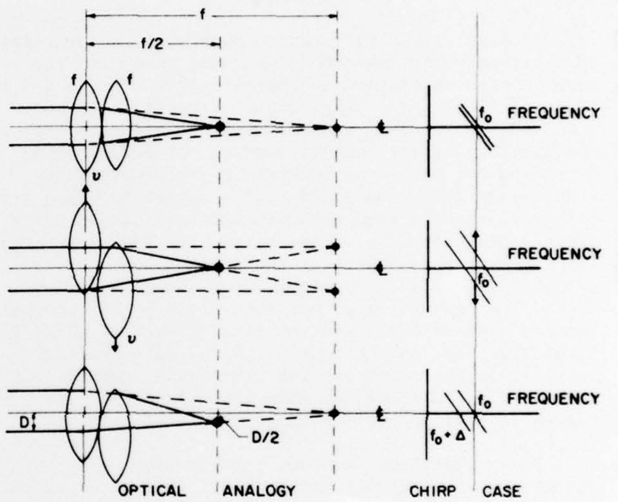


FIG. 3--Optical analogy for variable scan rate transmitter.

Let us consider the system shown in Fig. 2 mathematically. Suppose that two signals with frequencies $\omega_A = \omega_1 + \mu t$, $\omega_B = \omega_2 - \mu t$, are inserted into the ends A and B of the surface wave delay line, respectively. At a position y_n from the center of the line, the phases of the signals are:

$$\Phi_A(y_n) = \omega_1\left(t - \frac{y_n}{v} - \frac{L}{2v}\right) + \frac{1}{2}\mu\left(t - \frac{y_n}{v} - \frac{L}{2v}\right)^2$$

$$\Phi_B(y_n) = \omega_2\left(t + \frac{y_n}{v} - \frac{L}{2v}\right) - \frac{1}{2}\mu\left(t + \frac{y_n}{v} - \frac{L}{2v}\right)^2 \qquad (1)$$

respectively, where L is the length of the delay line, and v is the surface wave velocity. The parameter μ is the chirp rate. These signals are detected by the taps, amplified and mixed in the nonlinear elements. The phase of the signal (at the difference

frequency) after mixing is:

$$\Phi_d = (\omega_1 - \omega_2)t - (\omega_1 + \omega_2)\frac{y_n}{2} - (\omega_1 - \omega_2)\frac{L}{2v} + \mu\left[t^2 + \frac{y_n^2}{v^2} + \frac{L^2}{4v^2} - \frac{L}{v}t\right] . \quad (2)$$

The parabolic y_n^2 term provides the focusing. However, we would like to illuminate the object field with a signal of constant frequency so that narrow band transmitting transducers can be used with as little aberration as possible. A fixed center frequency gives a fixed focal length and hence small aberrations. We must, therefore, eliminate the time varying terms in the above equation. To this end, one tap at point y_0 of the delay line is used as a reference, as shown in Fig. 2. The signals from this tap are amplified and mixed with another frequency ω_0 (ω_0 will turn out to be the desired 2.25 MHz acoustic frequency). Hence, the output at point y_0 in the circuit is identical to that of Eq. (2) except that the frequency is shifted by ω_0:

$$\Phi_c = (\omega_1 - \omega_2 \pm \omega_0)t - (\omega_1 + \omega_2)\frac{y_0}{v} - (\omega_1 - \omega_2)\frac{L}{2v} + \mu\left[t^2 + \frac{y_0^2}{v^2} + \frac{L^2}{4v^2} - \frac{L}{v}t\right] . \quad (3)$$

This signal is then further amplified, filtered to retain only one of the sidebands, and applied across all the other mixing elements in the device. The difference frequency is employed to drive the transducers. If $y_0 = 0$, the resulting electrical phase at a frequency of ω_0 is given by the relation:

$$\Phi(y_n) = \omega_0 t - (\omega_1 + \omega_2)\frac{y_n}{v} + \frac{\mu y_n^2}{v^2} . \quad (4)$$

Thus we obtain an output to dirve the transducers with a fixed frequency ω_0 with a parabolic variation of phase.

If x_0 is elsewhere on the line, there is an additional constant phase shift term. This has no effect on focusing, because the focusing depends only on the difference in phase shift between taps. In the experiments described later, the reference was not at the center but at one end of the delay line.

Now consider the phase of the signal reaching a line a distance z away from the array at the point y in the field. The phase at this line is determined by the different propagation times from the various elements. Hence, the phase of the signal arriving at y , z from the element at y_n is

$$\Phi_n(y,z) = \omega_0\left[t - \frac{z}{v_w} - \frac{(y_n - y)^2}{2zv_w}\right] + \frac{\mu y_n^2}{v^2} - (\omega_1 + \omega_2)\frac{y_n}{v} , \quad (5)$$

where v_w is the sound velocity in water.

The chirp rate μ is chosen to be

$$\mu = \frac{\omega_0 v^2}{2zv_w} . \quad (6)$$

The term in $\Phi(y,z)$ which varies quadratically with y_n is cancelled out, and we find that

$$\Phi_n(y,z) = \omega_0\left[t - \frac{z}{v_w} - \frac{y^2}{2zv_w}\right] + \left[y_n\left(\frac{\omega_0 y}{2v_w} - \frac{(\omega_1 + \omega_2)}{v}\right)\right] . \quad (7)$$

Thus the transmitter focuses in a similar way to the receiver. We see all the signals from the 29 elements are in phase if

$$\left[\frac{\omega_0 y}{2v_w} - \frac{\omega_1 + \omega_2}{v}\right] \ell = 2m\pi , \quad (8)$$

where ℓ is the element spacing.

If we define $(\bar{\omega}_1 + \bar{\omega}_2)$, such that this condition occurs at $x = 0$, then we can write

$$x = (\omega_1 - \bar{\omega}_1)\frac{v_w}{v} z . \quad (9)$$

The frequency ω_1 corresponds to the actual carrier frequency of one of the surface waves, $\bar{\omega}_1$ to the carrier frequency required for the focus to occur at $x = 0$, and ω_2 is assumed fixed at $\bar{\omega}_2$. Hence, scanning is achieved by changing the frequency ω_1 with time — at a rate which is arbitrary.

We may summarize the operation of this method of focusing by noting that the focal length of the system is determined by the chirp rate, but the lateral y position of the focal point is determined by the carrier frequency ω_0 and the device may be scanned at an arbitrary rate by varying the frequency ω_1 either manually or by using a sweep generator.

III. The Experimental System

(a) Transmitter and Receiver Circuits

The receiver array used in the two-dimensional electronically focused device consisted, for simplicity, of a 22-element prototype transducer array of the type being developed for the 100-element system. In the same way, the receiver circuit consisted of a fairly crude prototype of the 100-element receiver circuit. It employed transistor amplifiers on every receiver element and amplifiers on every acoustic delay line tap. In the 100-element systems balanced integrated circuit mixers were used. Here, in order to save time and to demonstrate the principles of the focusing system, we made use of diode mixers. Our aim was only to make a demonstration of the two-dimensional electronic system, with the viewpoint that in the end we would use the 100-element receiver system presently being developed with our 29-element transmitter array. Suffice it to say that the 22-element receiver used was only large enough to obtain a field-of-view of approximately 1", but the quality of focusing and the level of sidelobes was excellent and the results were what would have been expected theoretically for a system with this small number of elements.

A block diagram of the transmitter has been shown in Fig. 2. One tap of the delay line is used to provide a frequency reference signal for the other amplifier mixer assemblies. This is done so that the outputs to the transmitter elements remain at a constant frequency with only a varying phase term. This frequency reference signal is derived by using one of the rf amplifier-mixer assemblies with no input at input "C" (see Fig. 2). This signal is then balance modulated with 2.25 MHz in a crystal diode mixer passed

through a filter to retain only the upper sideband, and applied in parallel to all of the other rf amplifier-mixer assemblies at the "C" input.

The system requires two FM chirp inputs, one to each end of the delay line, one chirp has a chirp rate μ , the other a chirp rate $-\mu$. We obtain the required signals by using a master FM chirp oscillator with a center frequency of 250 MHz. This is mixed in two separate mixers with two local oscillators of center frequency 203 MHz and 304 MHz, respectively. The signals obtained are therefore a positive chirp with a center frequency of 47 MHz and a negative chirp with a center frequency of 54 MHz. When these signals are inserted in each end of the delay line and mixed, they give rise to a chirp signal with a chirp rate 2μ and a center frequency of 7 MHz. The difference in these frequencies is chosen so that it is not too wide for the band pass of the delay line and it is not too narrow to give rise to difficulties with spurious frequency components.

The reference signal obtained from one tap is modulated with 2.25 MHz, as already described, and a signal of frequency 9.25 MHz is obtained. When this signal, in turn, is mixed with the 7 MHz signal at each tap, it gives rise to the 2.25 MHz signal required. This signal has the appropriate phase shift from tap to tap. When the chirp rate is changed, the square law variation along the system is varied in the appropriate manner for focusing. When one of the signals, either the 203 MHz oscillator or the 304 MHz oscillator is varied in frequency, an additional linear phase shift is superimposed on the square law phase shift in the system and the device can be scanned in this manner. By changing the oscillator manually, the device can be scanned manually at will or focused on a fixed point. By using a voltage controlled oscillator for one of these reference oscillators, the device can be scanned slowly electronically. Typically, we use a scan signal with a period of the order of 16 msec so as to obtain a 60 cps frame rate.

The transmitter circuit is shown in Fig. 4. Two gate FET's are used as amplifiers, and the mixing is carried out in a diode following the FET's. The difference frequency obtained is amplified by the power amplifier and used to drive the individual PZT element. A potentiometer is used to equalize the output amplitudes of the signals entering the individual transmitter elements. The receiver transducers were arranged in a horizontal line, and the point of intersection of the vertical line focus with the horizontal transmitter line focus is defined as the point being imaged. The oscilloscope intensity was modulated by the signal generated in the receiver. Hence, the electron beam intensity was proportional to the acoustic amplitude transmitted at the defined point of the object field. The vertical axis of the oscilloscope was driven by the ramp generator used to generate the scan signal for the transmitter. The horizontal chirps and scanning of the oscilloscope were triggered from the receiver. Hence, the horizontal axis corresponded to the horizontal position of the defined point and the vertical axis to its vertical position.

Some acoustic images obtained using this technique are shown in Fig. 5. A letter "S" carved into a piece of rubber is shown in Fig. 5. The top photograph is the acoustic image and the bottom, an optical image. In Fig. 5(b), the word "Stanford" was imaged by successively exposing the photographic film as each letter of the word was positioned in front of the array. In all cases the letter was approximately 1" high, formed from 1/8" openings. As far as we are aware, these results are the first demonstration of real-time, two-dimensional electronic focusing. The quality of these first results is still crude because of the limited number of elements used and phase errors present in the transmitter circuit which was altered several times as we encountered difficulties with it.

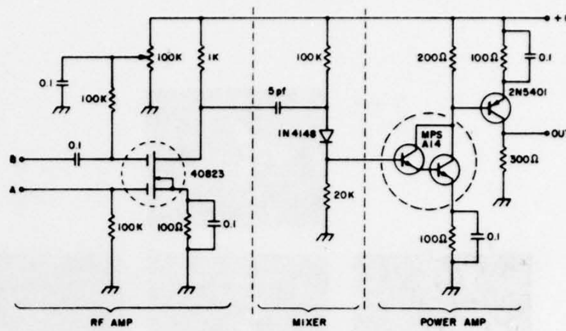
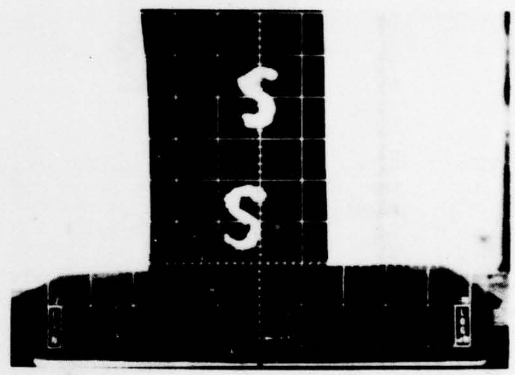


FIG. 4--Schematic diagram of amplifier/mixer assembly in the transmitter.



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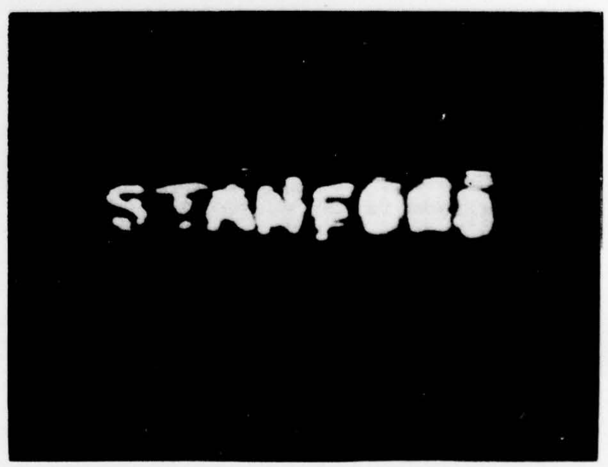

(b)

FIG. 5--Acoustic images obtained with the electronically scanned, electronically focused real time 2-D system. a) Image of the letter "S". Top figure is the acoustic result, bottom figure is the optical result. b) Image of the word "STANFORD".

Despite these problems the effect of defocusing is very apparent as can be seen in Fig. 6. Here we defocused the transmitter by changing the chirp rate by 25% thus defocusing the image in the vertical direction. Similarly defocusing in the receiver defocuses the system in the x direction.

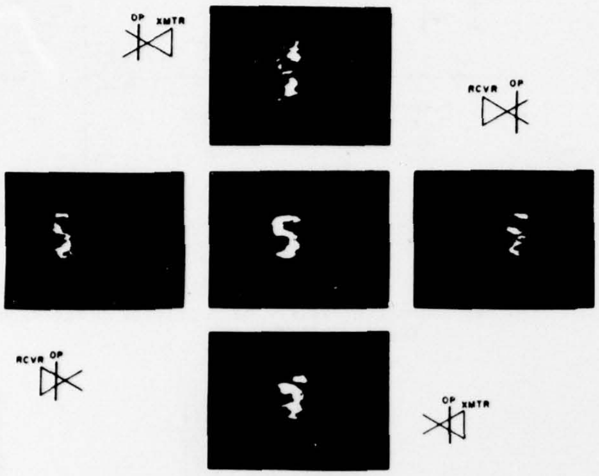

FIG. 6--Effect of a 25% defocus in the imaging system. Central picture is in the "in-focus" result.

Because the frame time is approximately 1/60 second, the image appears in real time. Hence, it is easy to observe the motion of the object as it is moved about the object field. It was also possible to scan the transmitters to any point designed, by varying the frequency ω_1 or ω_2 manually.

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